Efficient retrieval of a single excitation stored in an atomic ensemble

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We report significant improvements in the retrieval efficiency of a single excitation stored in an atomic ensemble and in the subsequent generation of strongly correlated pairs of photons. A 50% probability of transforming the stored excitation into one photon in a well-defined spatio-temporal mode at the output of the ensemble is demonstrated. These improvements are illustrated by the generation of high-quality heralded single photons with a suppression of the two-photon component below 1% of the value for a coherent state. A broad characterization of our system is performed for different parameters in order to provide input for the future design of realistic quantum networks.

A basic requirement for long distance quantum communication is the ability to efficiently interface atoms and light. Deterministic or heralded storage of light in atomic systems is essential for guaranteeing the scalability of protocols to distribute quantum entanglement over large distances, such as in the quantum repeater scheme [1]. In 2001, a significant step towards the realization of a quantum repeater was the proposal by Duan, Lukin, Cirac, and Zoller (DLCZ) of an alternative design involving atomic ensembles, linear optics, and single photon detectors [2]. The building block of this roadmap is a large ensemble of identical atoms with a Λ-type level configuration as sketched in Figure 1. A weak write pulse induces spontaneous Raman scattering of a photon in field 1, transferring an atom in the ensemble to the initially empty $|s\rangle$ ground state. For a low enough write power, such that two excitations to the $|s\rangle$ ground state are unlikely to occur, the detection of the field-1 photon heralds the storage of a single spin excitation distributed among the whole ensemble. A classical read pulse can later, after a user-defined delay, transfer this atomic excitation into another photonic mode (field 2). These scattering events are collectively enhanced thanks to a many-atom interference effect and can result in a high signal-to-noise ratio [3]. By following this line, nonclassical correlations [4, 5, 6, 7] and entanglement [8] have been observed between pairs of photons emitted by a single atomic ensemble. By combining the output of two different ensembles, as originally suggested in the DLCZ protocol, heralded entanglement between two remote ensembles has been recently demonstrated [9], paving the way for more complex implementations of DLCZ schemes. *A posteriori* (probabilistic) polarization entanglement between two distant ensembles has also been demonstrated recently [10], which does not lead to scalable capabilities for quantum networks.

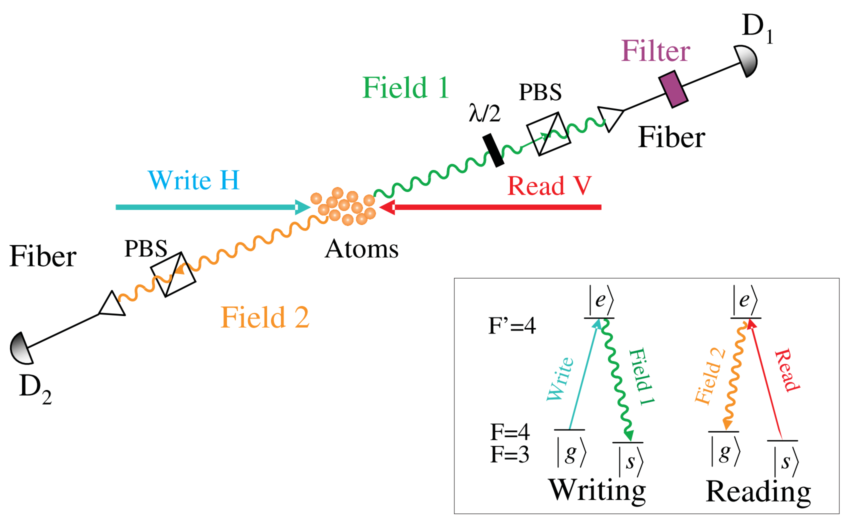

FIG. 1: Experimental setup. PBS stands for polarizing beam splitter, H and V respectively for horizontal and vertical polarization. The Filter stage for field 1 corresponds to a paraffin-coated vapor cell (see text for details). The inset illustrates the relevant atomic level scheme.

However, up to now, experiments have been plagued by low retrieval efficiency of the stored excitation and background noise. The low efficiency limits the extension to more complicated memory-based protocols, as their success relies on many-fold coincidences. Moreover, background noise prevents prior experiments from reaching the very low excitation regime, in which high photon-pair correlation and more pure conditional states can be obtained. We report here significant experimental progress to overcome these two limitations, which is crucial to enable realistic quantum

networks. As an illustration, high-quality heralded photons are generated. These conditional single photons are spectrally narrow and emitted in a well-defined spatio-temporal mode. They are thus well-suited for diverse interactions between light and matter [11, 12, 13].

The experimental setup is shown in Figure 1. The optically thick atomic ensemble is obtained from cold cesium atoms in a magneto-optical trap (MOT). The Cs hyperfine levels $\{|6S_{1/2}, F = 4\rangle, |6S_{1/2}, F = 3\rangle, |6P_{3/2}, F' = 4\rangle\}$ correspond to levels $\{|g\rangle, |s\rangle, |e\rangle\}$. The energy difference between the excited state and the ground states corresponds to a wavelength of 852 nm. The excitation and retrieval are carried out in a cyclic fashion. At a frequency of 40 Hz, the magnetic field is switched off for 5 ms. After waiting about 3 ms for the magnetic field to decay [7], a sequence of 1100 trials with duration 2 μs begins. For each trial, the atoms are initially prepared in level $|g\rangle$ by illuminating the cloud with trapping and repumping light for 0.5 and 1.1 μs, respectively. A weak write pulse, with a 200 μm beam waist, and detuned 10 MHz below the $|g\rangle$ to $|e\rangle$ transition, is first sent into the atomic sample. For a low enough excitation probability, the detection of a field-1 photon heralds the transfer of an atom from the $|g\rangle$ to the $|s\rangle$ ground state. The read pulse, which is on resonance with the $|s\rangle$ to $|e\rangle$ transition, orthogonally polarized with respect to the write beam and mode-matched to it, is then fired after a programmable delay. Both write and read pulses have about 30 ns duration. Fields 1 and 2 are directed into fibers with a 3° angle relative to the common direction defined by write and read beams [6], and with a waist of 50 μm for the projected mode in the atomic sample. This angle allows an efficient spatial filtering. Field 1 (2) is detected, with a polarization orthogonal to the write (read) beam, by single-photon silicon avalanche photodiodes (APD), and the electronic signals are sent to a data acquisition card, in order to record the detection events and analyze the correlations. At the end of the 5 ms sequence, a new MOT is formed. Note that, before detection, field 1 passes through a filtering stage, in which it goes out of the fiber, through a paraffin-coated Cs vapor cell, and back into the fiber [4]. The vapor cell is initially prepared with all atoms in $|g\rangle$. It filters out the photons in field 1 that are spontaneously emitted when the atoms in the sample go back to $|g\rangle$, which do not trigger the creation of the desired collective state.

An important figure of merit in studying the correlations in a photon-pair experiment is the normalized intensity cross-correlation function $g_{12} = p_{12}/(p_1 p_2)$, where p_{12} is the probability to detect a pair of photons, and p_i are the probabilities of detecting a single photon in field i. In our case, measuring a value of g_{12} larger than 2 is a strong indication of non-classical correlations [4, 7]. Another measure for the quality of the pair generation process is the degree of suppression w of the two-photon component of the field obtained from the retrieval of the collective excitation (field 2 conditioned on a detection in field 1), when compared to a coherent state [14, 15]. Another critical parameter to characterize the efficiency of the setup, as underlined before, is the ability to efficiently retrieve the stored excitation by firing a read pulse. We will denote q_c the probability to have a photon in field 2, in a single spatial mode, at the output of the atomic ensemble once an event has been recorded for field 1. The conditional probability p_c of having a detection event in field 2 is, of course, lower due to experimental losses from the atomic ensemble to the detector. If η is the overall detection efficiency for field 2, q_c and p_c are directly related by $p_c = \eta q_c$. For our setup, $\eta = 0.25$ due to 50% transmission loss in the field 2 pathway and the 50% detection efficiency of the APDs. The overall detection efficiency for field 1 is also around 0.25.

Note that, for a given degree of correlation characterized by g_{12} and w, the actual operation of a quantum information protocol, like the quantum repeater scheme proposed by DLCZ, can be evaluated based on the values for p_1, p_c, and the memory time of each site. A detailed analysis of the perspectives for memory time in our system has been addressed in a previous paper [7]. In the present work, we are more concerned with the other quantities, so that we fix our read/write delay at 300 ns.

Figure 2 gives the experimental data for g_{12}, the conditional retrieval efficiency q_c, and the joint probability p_{12}, as functions of p_1. The rate of coincidence counts per second can be obtained by multiplying p_{12} by the number of trials per second (44000 in our case). Note that all measurements reported in this paper are not corrected for any background or dark noise. The experimental points are fitted according to the model introduced in [15], which assumes that the total fields at the output of the MOT consist of a two-mode squeezed state plus background fields in coherent states (which change in proportion to the write field, such as light scattered from the write laser or background fluorescence from uncorrelated atoms that are also excited by the write beam) and two incoherent backgrounds to account for processes that do not depend on the write beam intensity (residual light from the environment or the MOT, and dark noise of the detectors). These results for g_{12} show more than a ten-fold improvement on previous reported experiments [4, 7, 8, 9, 10, 11, 12, 15]. For the highest value $g_{12} = 600 \pm 100$, the write pulse contains about 10^4 photons.

The shape of the q_c curve reveals different regimes for photon-pair generation. For high p_1, q_c decreases as p_1 is reduced, since the multi-excitation processes decrease with the energy of the write pulse. Once we reach the single excitation regime, q_c follows a plateau, since each detected field-1 photon (with whatever small rate) can lead to the subsequent detection of only one field-2 photon. In this regime, the probabilities for multi-excitation are negligible. When p_1 approaches the noise floor, however, q_c starts to decrease again due to false field-1 detection induced by the noise. From the plateau on the q_c curve, it results that the retrieval efficiency of a single excitation in our system is

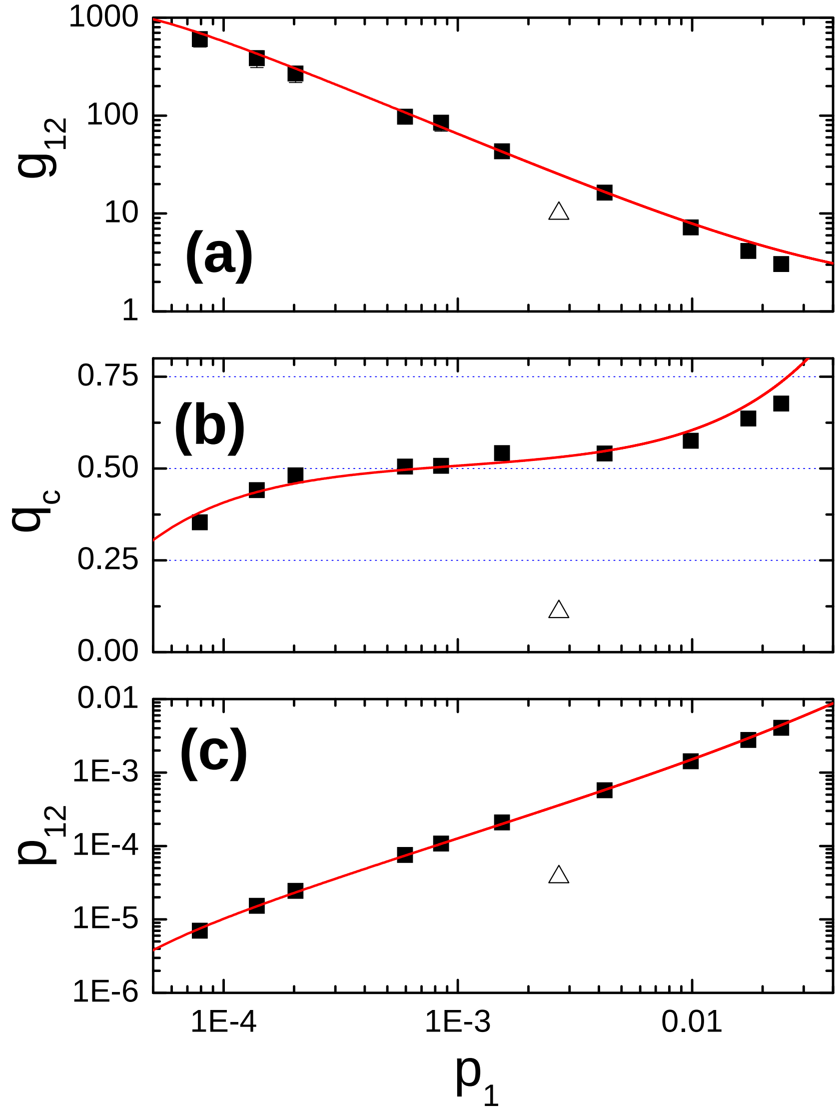

FIG. 2: Characterization of the system as a function of the probability p_1 to detect a photon from field 1. The frames give respectively the normalized intensity cross-correlation function g_{12} between fields 1 and 2, the conditional retrieval efficiency q_c, and p_{12}, which is the probability to detect a pair of photons, one in each field. The parameter q_c is obtained from the measured conditional probability p_c to detect field 2 once an event in field 1 has been recorded by the relation $p_c = \eta q_c$. The two points with lowest p_1 were obtained without trapping light (just repumper) between trials, in order to reduce the noise level. All error bars are smaller than the symbol size. The solid lines are from the simplified model of Ref. [15], with one set of parameters for all plots. The triangle indicates the experimental conditions for the entanglement measurement reported in Ref. [9].

approximately 50 % (corresponding to a measured $p_c = 12.5\%$). This value represents a three to five-fold improvement with respect to previous works [9, 11, 12]. We note that Ref. [16] has also investigated single-photon generation via the collective emission of an atomic ensemble, here coupled to an optical cavity. However, no direct measure of the single-photon character of the retrieved field 2 was given. Moreover, a retrieval efficiency was determined by way of the ratio p_2/p_1, which has, contrary to p_c, the drawback of being dependent on the characterization and modelling of the uncorrelated background fields. For instance, applying the same criteria to our measurements leads to a "retrieval efficiency" of around 160%.

As emphasized previously, the photon-pair correlations enable the generation of heralded single photons. This

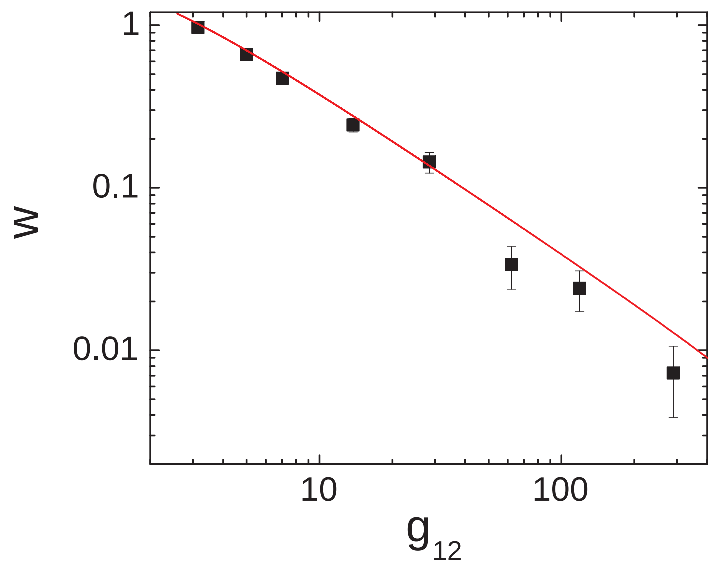

FIG. 3: Suppression of the two-photon component of field 2 conditioned on the detection events in field 1, measured by the w parameter, as a function of g_{12}. The lowest value obtained is 0.007 ± 0.003. All points in this plot were obtained without trapping light between trials. The full curve is from a fit based on the simplified model of Ref. [15], with the same parameters as in Figure 2.

method has been widely and very successfully used over the past decades, firstly with twin photons generated by an atomic cascade [14], then by using the more efficient technique of parametric down conversion [17]. More recently atomic ensembles were introduced as an alternative source of single photons [11, 12, 15]. To assess the quality of the single photon generated, a 50/50 fiber beam splitter (with 20% transmission loss) is inserted into the pathway of field 2, and two detectors, D_{2a} and D_{2b}, are used to record the events. Figure 3 gives the parameter w for the detection of two photons from field 2, conditioned upon the detection of an initial photon in field 1. This parameter measures the single-photon character of field 2. For both experiment and theory, this quantity was obtained from single and joint probabilities by the expression [14, 15]

$$w = \frac{p_1 p_{1,2a,2b}}{(p_{1,2a})(p_{1,2b})} \,, \tag{1}$$

where $p_{1,2a,2b}$ indicates the probability for a triple coincidence between the three detectors, and $p_{1,2a}$ ($p_{1,2b}$) gives the probability for coincidences between detectors D_1 and D_{2a} (D_{2b}). A best value of $w = 0.007 \pm 0.003$ is obtained. This represents more than a twenty-fold improvement on the first reported value [15], and ten-fold on the subsequent extensions [11, 12]. Furthermore, this value is close to the best reported ones in parametric down conversion [18, 19]. This low value makes this source relevant in the realization of linear-optics quantum computation [20], where two-photon contamination must be minimized. Note again that these photons are narrowband and thus well-suited for light-atom interfacing [11, 12, 13].

These large improvements were obtained after an empirical adjustment of the duration and energy (10^7 photons per pulse) of the read pulse, and an increased optical depth ($OD = 12$) of the ensemble. We also incorporated several improvements previously implemented by other groups, like the off-axis detection geometry (introduced by S. Harris's group [6] and later optimized by A. Kuzmich's group [8]) and the use of large-waist write and read beams [21]. We also found that it is essential to continue using the frequency filter in field 1. The lack of this filter in recent experiments that rely completely on postselection [8, 10, 11] might be responsible for an effective decrease of p_c and the measured correlations.

In conclusion, we have reported the efficient generation of photon-pairs from atomic ensembles, following the building block of the DLCZ roadmap. Apart from unprecedented nonclassical correlations in this configuration, we obtained high retrieval efficiency of the stored excitation around 50%, which is a critical parameter for the realization

of sophisticated quantum networks and memory-based protocols. The importance of having high p_c and q_c is clearly illustrated in Ref. [9], in which the small values of these quantities limits the ability to infer the degree of entanglement between the two distant ensembles.

Acknowledgments

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